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A Flexural Fatigue Machine for High-Temperature Operation at Resonance in Vacuum

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ABSTRACT

A resonance type reversed-bending, high-temperature fatigue machine for operation at constant bending amplitude in vacuum has been developed. The vibration frequency is maintained at resonance by means of a feedback circuit employing a capacitance pickup. Another circuit maintains a constant amplitude of vibration. As fatigue cracks are developed, the resonant frequency is reduced. Curves of resonant frequency versus time at 800°C for materials of high damping, such as Type 316 stainless steel, and for materials of low damping, such as Inconel X, illustrate the development of fatigue damage.

PROBLEM STATUS

This report completes one phase of the problem; work on other phases of the problem is continuing.

AUTHORIZATION

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A FLEXURAL FATIGUE MACHINE FOR HIGH-TEMPERATURE OPERATION AT RESONANCE IN VACUUM

INTRODUCTION

Recently, a number of machines have been developed for fatigue testing in vacuum and controlled environment, in response to the growing realization of the importance of environmental data for material application work and for investigations of the mechanism of fatigue (1-8). Of these machines, only one has been designed for operation in reversed bending at elevated temperature (2,3). In it the problem of moving seals was eliminated by using external electromagnets to vibrate the specimen; the electromagnets were manually tuned to the resonant frequency of the specimen assembly. Although this arrangement proved adequate for soft materials of high damping capacity, it was found to have shortcomings for work with elastic materials of low damping capacity. Highly elastic materials have such a sharp resonance peak that it was difficult to tune and hold to the correct frequency manually long enough to generate a visible crack. This report describes a feedback circuit for automatically keeping a specimen vibrating at resonance. In addition, significant improvements made in the feedback circuit controlling the amplitude of vibration are included here.

DESIGN DETAILS

Basic Features

The mechanical features of the machine are schematically shown in Fig. 1. Reversed-bending fatigue tests are performed on sheet-metal specimens fitted with an extension rod which removes the permanent magnet (or ferromagnetic material) from the heat zone of the external split furnace (not shown) which encloses the specimen. A traveling microscope (not shown) is used to measure the amplitude of vibration, which is adjusted by moving the gold contacts on the amplitude-adjusting mechanism in or out. There are two completely transistorized electrical feedback circuits (Fig. 2). One is the feedback circuit which keeps the specimen frequency at resonance, and the other comprises two loops for controlling the amplitude of vibration. As the permanent magnet at the end of the extension rod passes beneath the capacitor plates, a sine wave is generated. This signal is used to trigger the transistor switches, which pass current to the electromagnets at the correct frequency. The amount of current is governed by the amplitude-control circuit, which senses the vibration amplitude by the striking of the extension rod against the contacts. With the present 0.110-in.-thick specimen, extension rod, and permanent-magnet geometry, resonant frequencies in the 2 to 15 cps range are obtainable. Altered geometry and redesigned electromagnets would permit higher frequencies. Provision is made to terminate the test automatically. As a crack develops the frequency of vibration is reduced, and the test is terminated when the frequency reaches a preset value.

Regenerative Drive Loop

In Fig. 3, a functional diagram is given for the regenerative drive unit whose construction is detailed in Fig. 4. In brief, the sine wave from the C-Line Probe and Capacitance Transducer* is amplified, chopped, differentiated, and converted to two separate pulses which trigger the transistor switches, which in turn pass current to the electromagnets.

*Lion Research Corp., Cambridge, Mass.

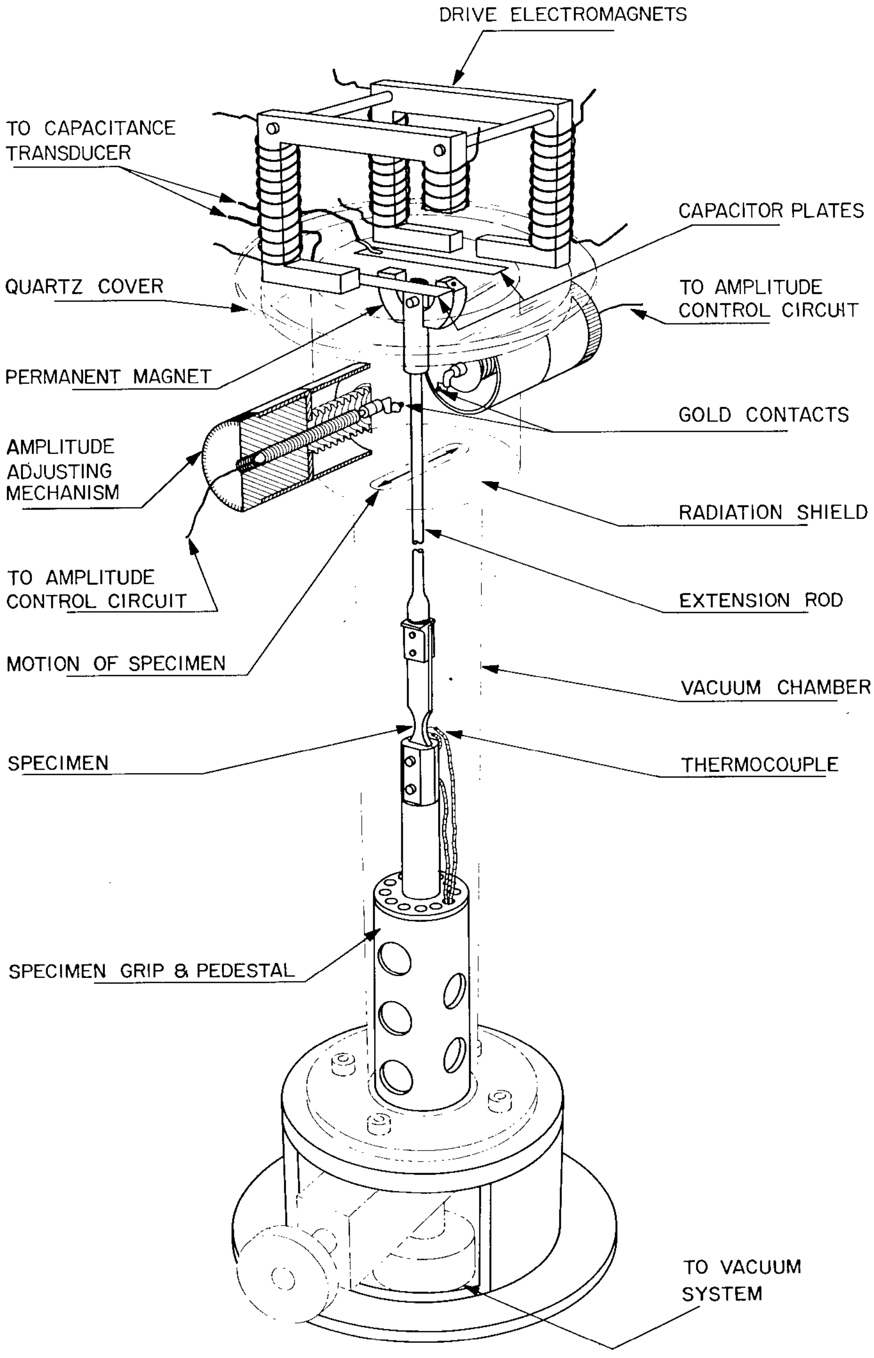

Fig. 1 - Mechanical features of fatigue machine

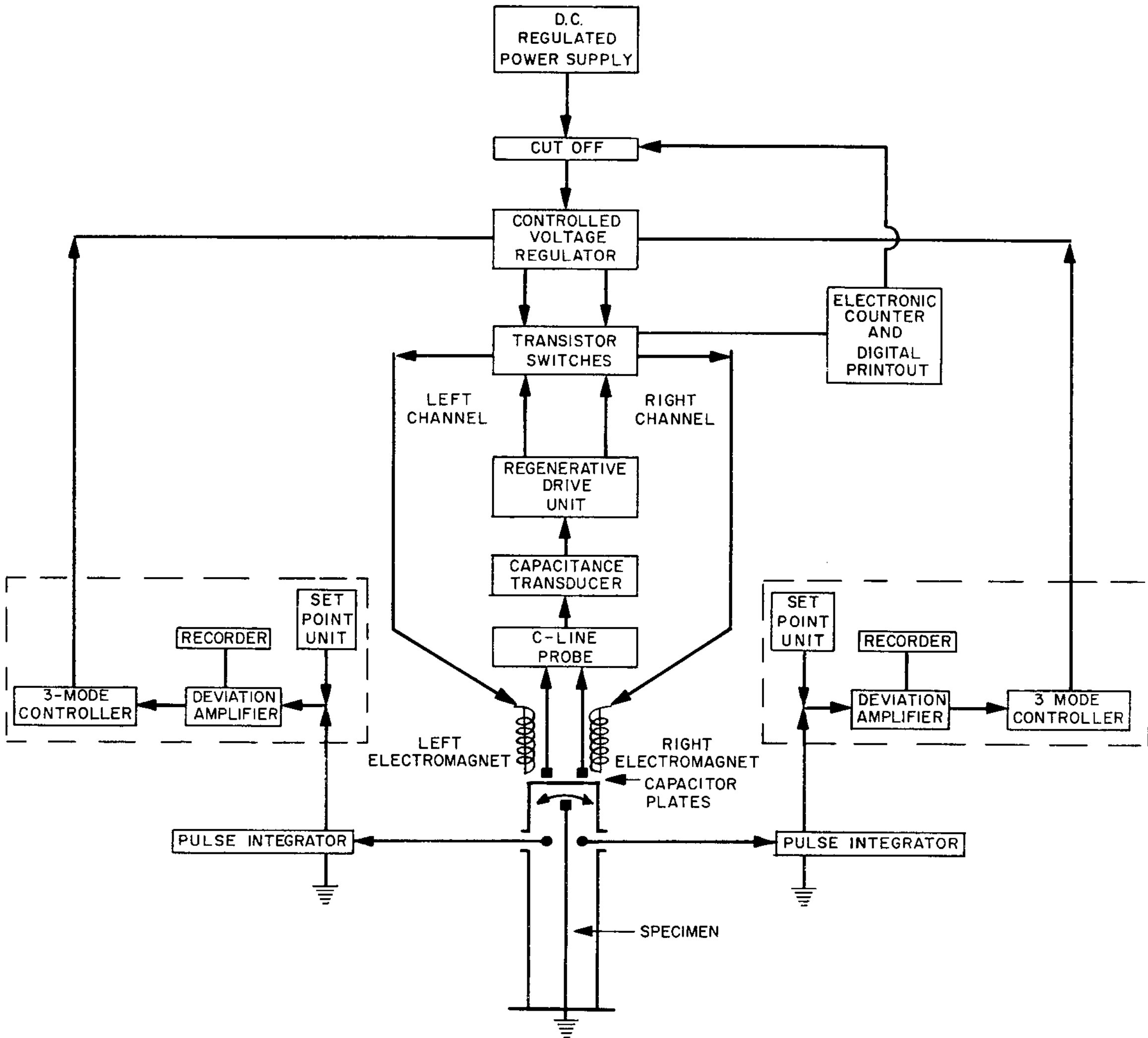

Fig. 2 - Block diagram of fatigue machine electronics showing feedback loops

A phase shifter is incorporated to vary the phase angle between the drive pulse and the permanent-magnet displacement, to provide the maximum amplitude for a given current.

Amplitude Control Loop

A constant amplitude of vibration is achieved by means of two loops whose sensing elements are the contacts in Fig. 5 and whose control elements are Minneapolis Honeywell precision set point three-mode control systems (Fig. 2). In the construction of the contact, a 0.050-in.-diameter gold bead is threaded on a 0.005-in. piano wire and soldered in place. Striking of the contact effectively closes the contact switch (Fig. 6) momentarily and charges the integrating capacitor. The level of charge depends on the length of time the switch is closed or, in practice, how hard the contact is struck. This voltage is compared to a reference voltage from the set-point unit (Fig. 2), and the difference is amplified in the deviation amplifier; an error signal is thereby provided for the three-mode controller. Current through the electromagnets is then varied in the controlled-voltage regulator (Fig. 7) by the output of the controller. Strip-chart recorders which monitor the

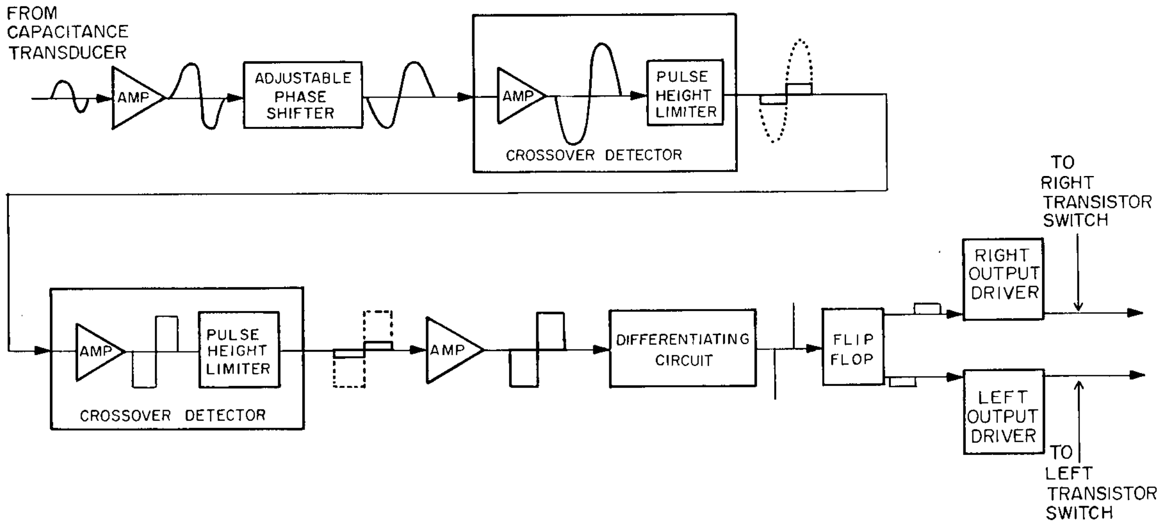

Fig. 3 - Functional diagram of regenerative drive unit

error signal from the deviation amplifier give an indication of whether the amplitude is above or below the desired value.

Electromagnets

The configuration of the electromagnets is shown in Figs. 1 and 8. Each coil consists of 2262 turns of No. 26 wire and has an inductance of 1 henry and a dc resistance of 40 ohms. The two coils for each side are wired in parallel and wound on a 3/8-in.-thick stacked core of EI-8, with a 3/4-in. air gap.

Frequency Recording and Automatic Shutoff

A Hewlett-Packard electronic counter and digital printout (Fig. 2) records the period of the pulses through the transistor switches. The digital printout also provides an analog output for driving a strip-chart recorder.

Automatic termination of the test at a predetermined frequency is effected by an "and" gate. A three-position dial switch, added to the printout, is set to the first three digits of the desired cutoff period of vibration. When the period is increased to this value the power to the controlled-voltage regulator is cut off.

Stress and Strain Measurements

For an elastic material such as Inconel X, the stress can be calculated by the Mc/I method (2). For softer materials, such as Type 316 stainless steel, it is preferable to measure the bending strain. An optical technique for this type of measurement has been described (9).

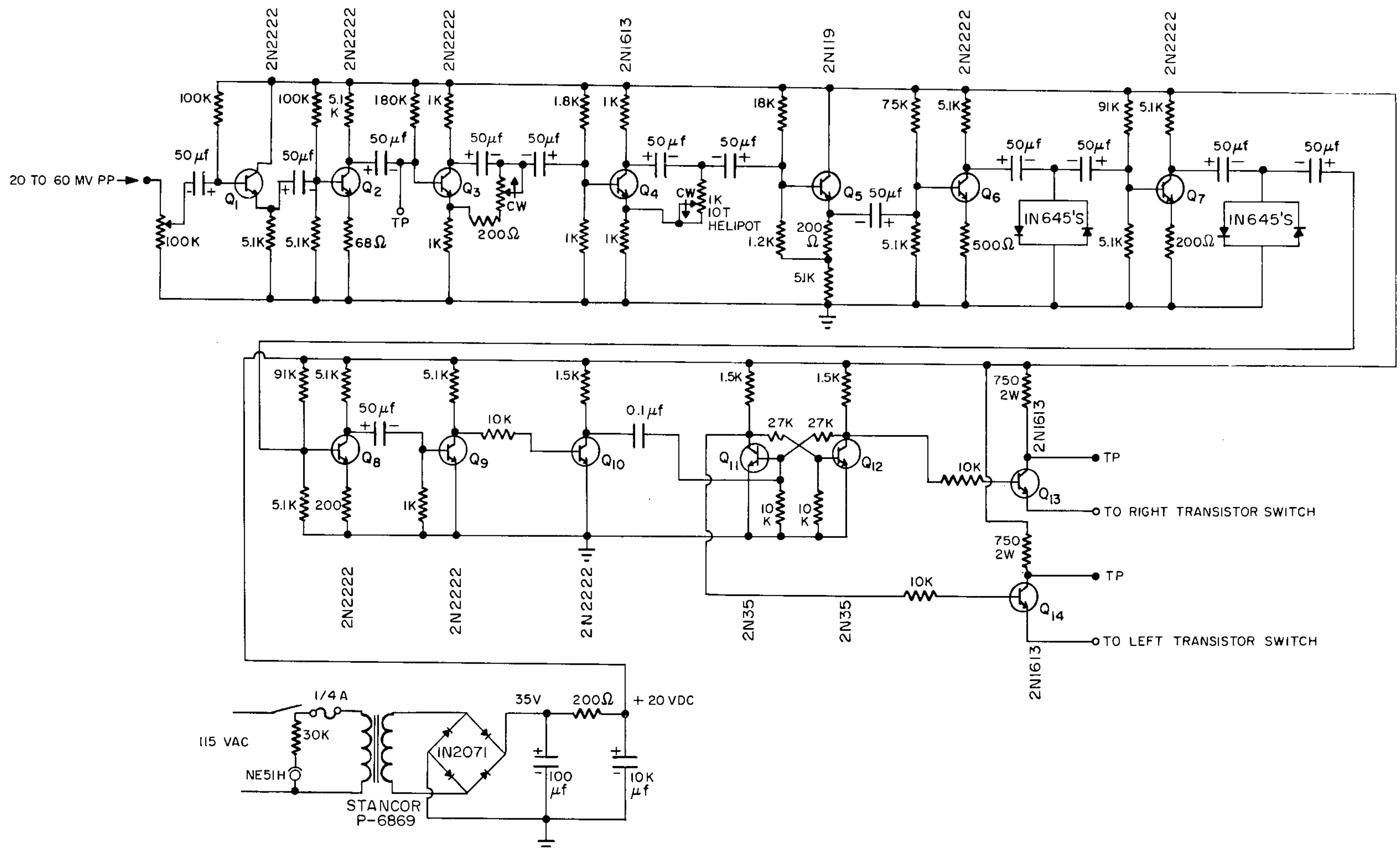

Fig. 4 - Schematic diagram of regenerative drive unit

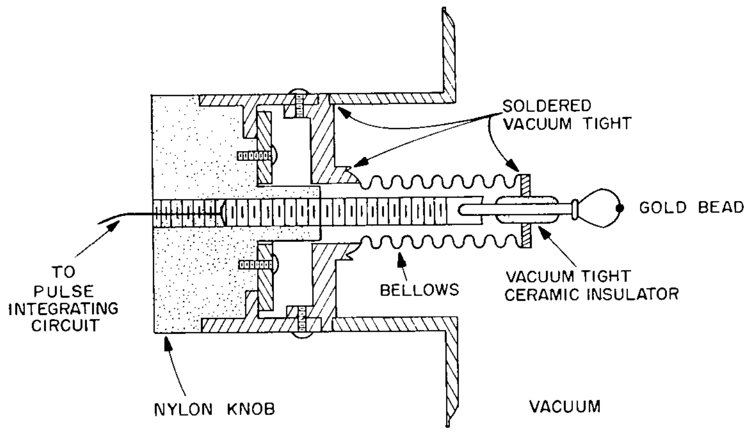

Fig. 5 - Amplitude adjusting mechanism and contact

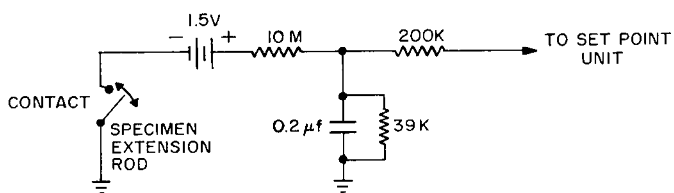

Fig. 6 - Schematic diagram of pulse integrator

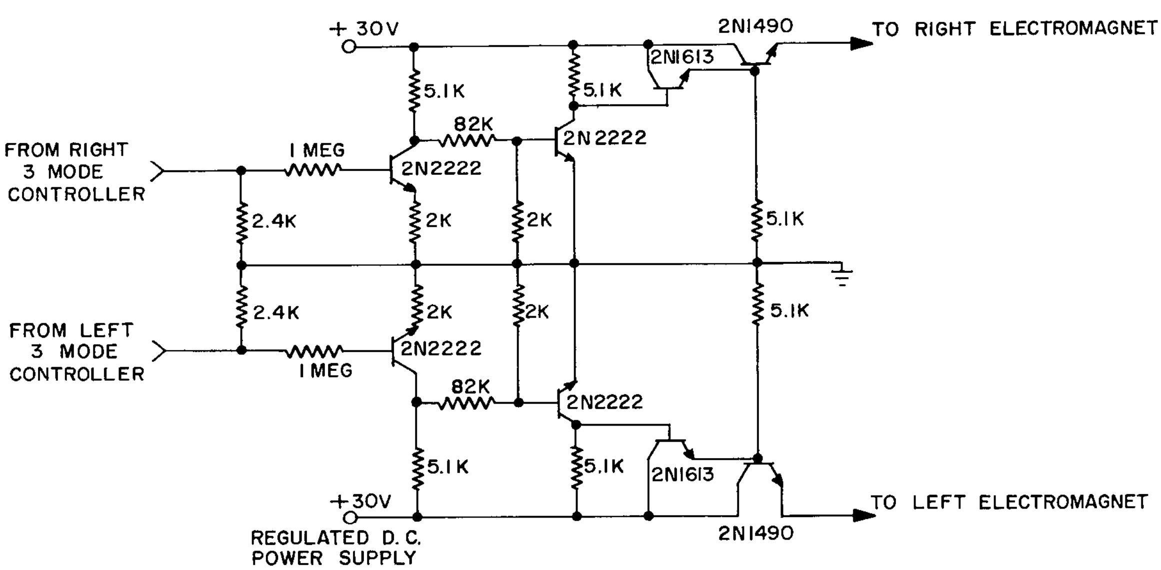

Fig. 7 - Schematic diagram of controlled-voltage regulator

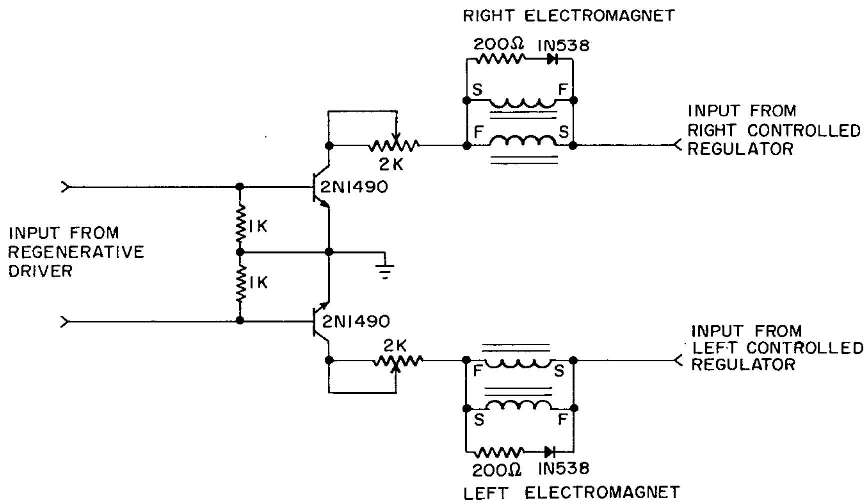

Fig. 8 - Schematic diagram of transistor switches and electromagnets

OPERATION AND RESULTS

Initial Startup and Calibration

Upon initial operation of the system, the right and left channel reference voltages generated by the set-point units (Fig. 2) must be balanced. This is easily accomplished as follows. With the specimen at rest, the set-point units are adjusted until both error signals are zero. Then the voltage outputs of the set-point units are increased an amount equal to the desired reference voltage. A high sensitivity is obtained by a low reference voltage, but a higher value is conducive to more stable operation. A value of 0.6 mv gives a good combination of stable operation and precise control of amplitude. Once this setting has been made, further adjustment of the reference voltage for succeeding tests is not needed.

It is also necessary to adjust the phase shifter for optimum operation. A convenient method of tuning the phase shifter is to raise the manual output adjustments on the three-mode controllers (Fig. 2) to give a constant amplitude. The phase shifter (Fig. 3) is then adjusted to give the maximum amplitude of vibration. This amplitude is developed at the resonance frequency under forced vibration. It has been found that the vibration is more stable if the phase shifter is adjusted to produce a frequency slightly lower than resonance. Once the phase angle has been adjusted, it needs no more attention in successive tests until the material under test or the temperature of operation is changed.

Routine Operation Procedure

It is important that the specimen mount and clamp (Fig. 1) be rigid and tight. Any looseness, even an imperceptible amount, can result in poor amplitude control. After an overnight pumpdown, the furnace is brought to temperature and held there until the operating vacuum of 1×10^{-6} torr is reached. The amplitude of vibration is raised by means of the manual adjustments to a level slightly below the test amplitude. Both contacts are moved inward until the deviation-amplifier recorders are at zero. Automatic control of the amplitude of vibration is begun by switching the three-mode controllers to automatic, and the contacts are then retracted until the desired test amplitude is reached.

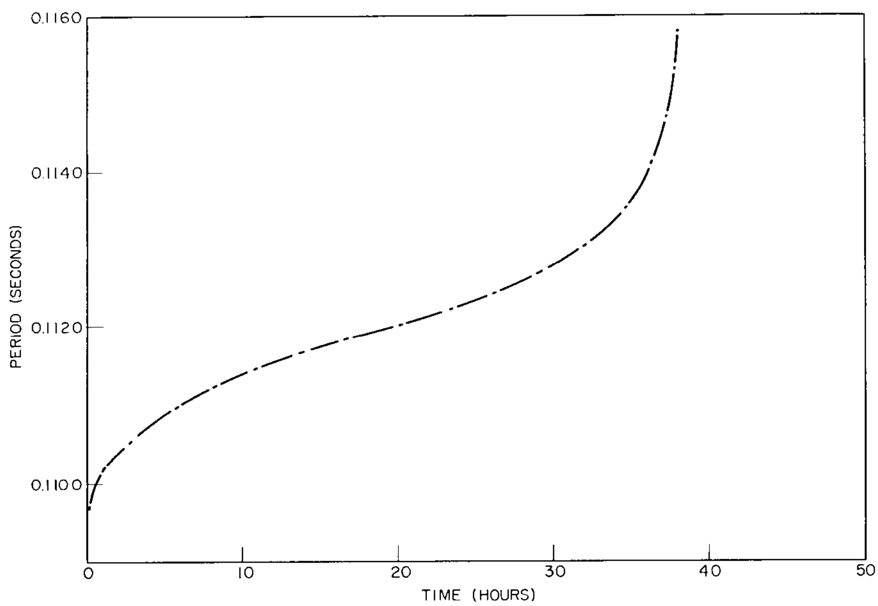

Fig. 9 - Variation of period of vibration with time for Inconel X at 800° C and a strain amplitude of 0.156 percent

Hard and soft materials do not respond similarly to the electromagnetic drive. For example, with a hard material such as Inconel X care must be taken that no overshoot is encountered in coming up to the test amplitude. With a softer material, such as Type 316 stainless steel, there is no such problem. With softer materials there is the possibility of some creep at temperatures of the order of 800°C, therefore two-channel control of the amplitude of vibration is necessary. Inconel X, however, does not have this tendency, in that temperature range and testing can be accomplished with only one channel control. Elimination of one of the channels considerably simplifies the equipment and testing procedure.

Results

Although the characteristics of the two materials are somewhat different, the accuracy of amplitude control is about the same for both. Any short-term cycling or long-time variation due to drift in the electronic instrumentation or deformation of the contacts can be measured directly only by readings with the traveling microscope. Any such variations are, for an amplitude of 0.4 in., within the reproducibility of readings with the microscope, which is 0.001 in. Therefore, the overall consistency of amplitude is within 0.25 percent. Since the frequency of vibration is a function of amplitude, decreasing as the amplitude increases, the constancy of the frequency of vibration may be used as an indication of the amplitude control. According to the electronic counter the period of vibration is constant to 0.04 percent.

Typical curves of the period of vibration versus time for Inconel X and Type 316 stainless steel at 800°C are shown in Figs. 9 and 10. These curves are obtained from the record of the digital printout. It is evident that crack propagation, once begun, proceeds rapidly, as indicated by the sharp upturn of both curves toward the end of the fatigue test. A metallographic study is being started to relate the slopes of the curves to the various stages of crack nucleation and growth. It is expected that the history of the development of fatigue damage may be read from one such curve and may at times be used to substitute

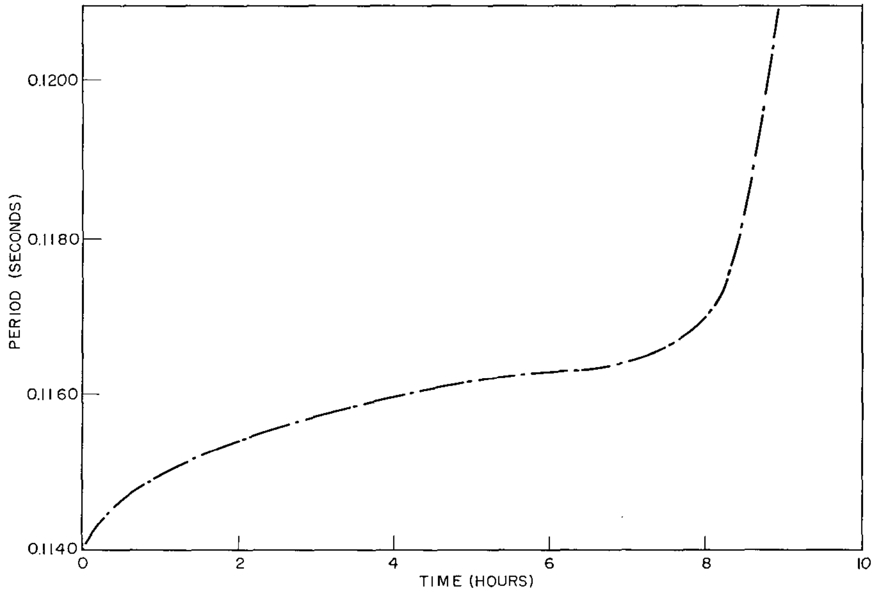

Fig. 10 - Variation of period of vibration with time for Type 316 stainless steel at 800°C and a strain amplitude of 0.184 percent

for the laborious metallographic examination of a series of specimens interrupted at various stages of the test.

DISCUSSION

After more than six months of operation, the equipment has proved relatively simple to operate and to be reliable. Other than setting of the amplitude of vibration, there are only two adjustments to make. The reference voltage needs to be adjusted only at the initial startup. Tuning of the phase shifter is required only when the material or temperature of testing is changed. Since there are no mechanical parts to wear out, the equipment is trouble free, and since it has been fully transistorized, there have been no shutdowns because of trouble with either regenerative drive or amplitude-control loops.

The precise control available for the cutoff frequency suggests another application for this apparatus. Frequently, starter cracks are desirable when mechanically testing high-strength steels. With these materials, however, it is often difficult to stop the crack before it has propagated completely through the specimen cross section. It should be possible to obtain very consistent starter cracks by setting the cutoff for a predetermined frequency change.

ACKNOWLEDGMENT

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